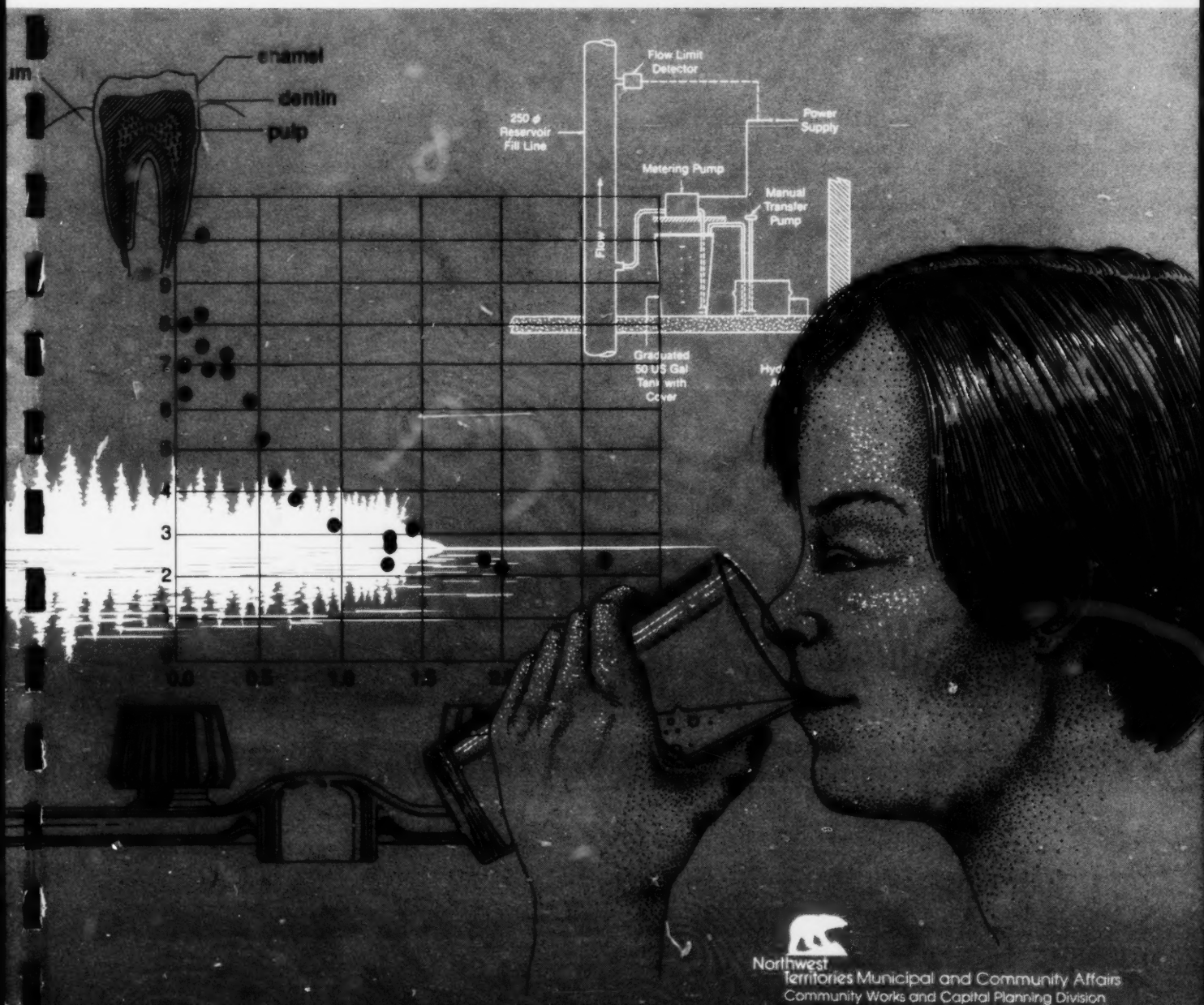
Fluoridation of Water Supply Reservoirs
in the Northwest Territories

by M.L. Murray and G. W. Heinke



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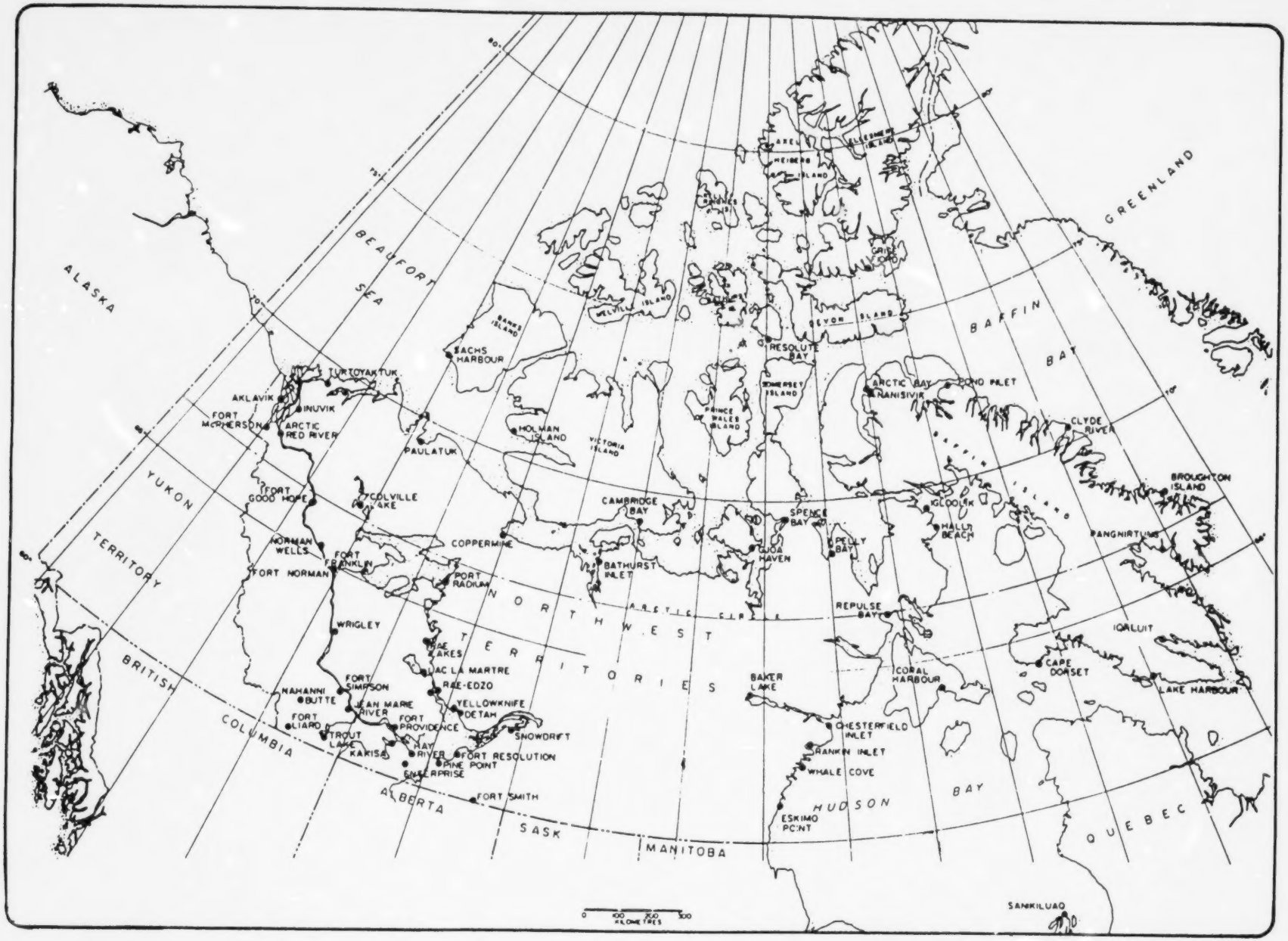
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FLUORIDATION OF WATER SUPPLY RESERVOIRS IN THE NORTHWEST TERRITORIES

A research report prepared by

M. L. MURRAY and G. W. HEINKE

For

The Department of Municipal and Community Affairs
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Executive Summary

The poor state of dental health and the high incidence of tooth decay in the Northwest Territories (N.W.T.), particularly among native people, is a cause for considerable concern. Tooth decay can be reduced by a combination of good nutrition, improved oral hygiene and the use of fluoride supplements. There are numerous methods of supplementing the normal dietary intake of fluoride. The most equitable, effective and efficient method is to add a controlled amount of fluoride to community water supplies. Although N.W.T. regulations recommend that community water supplies be fluoridated, only 4 communities currently practice fluoridation. Because of the variety of water supply systems in the N.W.T., various techniques of water fluoridation are required.

This study examined, in detail, water fluoridation in those communities with water storage reservoirs which are filled once each year (i.e. provide year-round storage). A "batch fluoridation" approach is recommended, in which fluoride is added, to the reservoir fill line, during the annual reservoir filling. The necessary equipment is described, and conceptual designs are presented for the batch fluoridation systems. The calculation of the appropriate fluoride dose in each community

requires information such as: fluoride concentration of the water source and existing reservoir water, the depth/area/volume relationships for the reservoir, the monthly water consumption from the reservoir, and the expected monthly ice growth on the reservoir.

This report also briefly describes the first implementation of batch fluoridation, in Tuktoyaktuk, N.W.T. This demonstrated the feasibility of batch fluoridation, and provided some operational experience with the process. Extensive monitoring was done during the reservoir fluoridation, and further monitoring is recommended. This study showed that water fluoridation in communities with year-round reservoir storage can be done safely and successfully using the batch fluoridation method. Considerable government effort is now required to promote fluoridation and ensure its implementation in an efficient, effective manner.

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1.0 INTRODUCTION

1.1 Background

This report is the result of work done in 1986 and 1987 by researchers at the University of Toronto. Marianayagam (1986) examined the status of dental health and water fluoridation in the Northwest Territories (N.W.T.). His report discussed fluoride supplements in general, and presented various methods of water fluoridation, compatible with a variety of water supply systems. His work is summarized in a report entitled "Dental Health and Fluoridation in the Northwest Territories" (Marianayagam, Heinke and Murray, 1988). Readers interested in background information on dental health and fluoride supplements in the N.W.T. should consult that report.

Subsequent work by Murray (1987) examined the fluoridation of water supply reservoirs in the N.W.T.. His report described the design of a "batch fluoridation" system for water supply reservoirs, and discussed the first implementation of batch fluoridation in the N.W.T.. His work is summarized in this report.

1.2 Dental Health and Fluoride Supplements

Several studies have documented the poor state of dental health, and the alarming prevalence of dental caries in the N.W.T., particularly among native people. Mayhall (1984) claimed that

"By any measure of oral health .... dental caries and periodontal disease are probably the most prevalent diseases of arctic residents". Dental caries is the widespread, multi-factorial disease which causes most tooth decay. It begins with the formation of acid by microorganisms in the layer of plaque (sticky substance composed of saliva and tiny bits of food residue) overlying the tooth enamel. The acid acts to dissolve the tooth enamel, creating a cavity in the tooth surface (tooth decay). It is a localized, multifactorial disease requiring the simultaneous presence of three factors:

(1) microorganisms,

(2) a diet for the microorganisms, and

(3) a susceptible host or tooth surface

(Mellberg and Ripa, 1983).

The caries process can be curtailed in several ways. First, improved oral hygiene can reduce the number of cariogenic bacteria or disrupt their ability to metabolize fermentable carbohydrates. Secondly, reducing the dietary intake of sucrose will reduce the substrate available for bacterial action. Finally, the ability of the tooth to withstand caries attack can be enhanced by the ingestion of the proper amount of fluorides.

Evidence suggests that fluoride provides anticaries action in several ways, and that several mechanisms may function simultaneously. Fluoride can modify, or eliminate each of the

three factors previously mentioned as necessary for caries formation. Some contributions of fluoride to caries resistance include:

(1) increased enamel resistance,

(2) increased rate of tooth maturation, and

(3) remineralization of enamel.

The normal dietary intake of fluoride can be supplemented in several ways to enhance caries protection. Fluoride supplements may be either systemic or topical. Systemic fluoride enters the body's digestive system via food, water or fluoride tablets and acts from the "inside-out". The fluoride is incorporated within the enamel of developing teeth, providing maximum caries resistance. Topical fluoride works from the "outside-in". Topical fluoride treatments are applied directly to teeth as solutions, gels, varnishes, or via the use of toothpastes. Because topically applied fluorides do not penetrate deeply into the enamel, they tend to provide only local protection at, or near, the tooth surface (Newbrun, 1986). They do not provide nearly the same degree of caries protection as systemic fluoride supplements.

From a public health perspective, an ideal fluoride supplement should benefit the entire population of a community, regardless of age, social class, economic status or access to dental care. Furthermore, it should be available during the critical period of

tooth development (birth to 8 years), should be economical, and require minimum effort from those receiving the benefits. On the basis of these and other criteria, numerous studies have concluded that fluoridating community water supplies, where possible, is the desired method of providing a systemic fluoride supplement.

1.3 Water Fluoridation in The N.W.T.

The revised regulations of the N.W.T. (1980, No. 218; pursuant to the Public Health Act, 1985) recommend that community water supplies contain between 1.2 and 1.6 mg/l fluoride; with an optimum concentration being 1.4 mg/l. The natural fluoride content of fresh water in the N.W.T. is generally quite low (approximately 0.1 mg/l). Thus to achieve the optimum fluoride concentration of 1.4 mg/l, most communities would have to add fluoride supplements to their water supplies. However, for a variety of reasons, only four communities (Fort Smith, Iqaluit, Inuvik and Yellowknife) currently practice water fluoridation. This is due, in part, to the diversity, and relative lack of sophistication of water supply systems in the N.W.T.

Marianayagam (1986) reviewed the existing water supply systems in the N.W.T., and proposed that water fluoridation be implemented in 30 additional communities. His work is summarized in Table 1.1, and discussed briefly below.

TABLE 1.1

WATER FLUORIDATION IN THE N.W.T.

(after Marianayagam, 1986)

Water Supply/ Treatment	# of Comm'ties	Pop'n (%)	Current Status of Fluoridation	Recommendations
Conventional Treatment	11	17344 (34)	3 communities currently fluoridate	Fluoridation using conventional technology (8 additional communities)
Disinfection Only; No year-round storage	34	25506 (50)	1 community currently fluoridates	Fluoridation only if monitoring/control possible (12 additional communities)
Disinfection Only; Year-round storage	10	7652 (15)	No fluoridation	Batch fluoridation during reservoir filling (10 additional communities)
No service provided	8	510 (1)	No fluoridation	Fluoridation not recommended
TOTALS	63	51012 (100)	**4 communities (35% of pop'n)**	**Fluoridation recommended in 30 additional communities (23996 additional people)**

In the 11 communities with conventional water treatment plants, fluoridation, if not already practiced, could easily be implemented using conventional technology. In such facilities fluoride is usually added continuously to the filter effluent lines or to a clear well, following treatment. Several of the water treatment plants are self-contained package plants, which could be easily modified to incorporate fluoride addition. Fluoride must be added at a location which avoids recirculation, and must be monitored frequently (e.g. once/day).

In most communities in the N.W.T., disinfection is the only water treatment practiced. Some of these communities have year-round reservoir storage facilities but the majority do not. In those communities with no year-round storage, fluoridation was recommended only if the configuration of the supply system would allow for adequate monitoring and control of the fluoridation process (12 communities). This generally occurs where a holding tank is provided following chlorination and prior to water distribution (trucked or piped). The fluoride injection point would have to be located so that water to be fluoridated did not include water from a recirculation line. It was not recommended that fluoride be added during the filling of water trucks at a truckfill station. The reasons for this will be discussed shortly.

As indicated in Table 1.1, 10 communities in the N.W.T. practice only disinfection and have year-round water storage facilities. Marianayagam (1986) discussed several possibilities for fluoridating such water supplies including:

(1) metering a fluoride solution into the water on the discharge side of the distribution pump, while filling a water truck tank, or feeding the pipe network,

(2) addition of fluoride in tablet form to the water truck tank, where it would dissolve during transport,

(3) addition of a measured quantity of fluoride solution to the water truck tank,

(4) a system whereby a fluoride tablet would be placed in a sieve located in the truckfill line with the fluoride dissolving as the truck was filled with water,

(5) addition of fluoride to the entire reservoir after filling,

(6) addition of fluoride during the annual reservoir filling.

Alternatives (1) to (5) have serious drawbacks, generally relating to the need for relatively skilled operation of the system, maintenance requirements and ensuring adequate mixing of the fluoride chemical with the water, either in a truck tank or in the entire reservoir. The problems are compounded by the fact that the fluoride imparts no taste, odor or color to the water (unlike chlorine). Thus, fluoride overdoses would be very difficult to detect without chemical analysis.

The final alternative involves adding fluoride to the water during reservoir filling. This "batch fluoridation" alternative was recommended for the following reasons:

(1) Thorough mixing of the fluoride chemical with the water would take place due to the turbulence in the supply line between the point of injection and the storage reservoir,

(2) The fluoridation of the water would be done once each year, and thus would require skilled supervision for a relatively short period of time, while the reservoir is being filled.

A complication of this system is the tendency for the fluoride concentration in the water to increase as ice forms on the reservoir during the winter. This phenomenon and its implications are discussed further in Chapter 2.3.

The remainder of this report deals with batch fluoridation of water supply reservoirs. As mentioned previously, ten communities in the N.W.T. are serviced by year-round water storage reservoirs. Eight of these ten communities were examined in detail by Murray (1987), namely: Tuktoyaktuk, Pangnirtung, Broughton Island, Igloolik, Coral Harbour, Eskimo Point, Fort Good Hope and Grise Fiord. Pine Point and Hall Beach were not considered; Pine Point because the community may soon be abandoned as the result of a mine closure, and Hall Beach because its reservoir/lake is refilled each year by natural recharge, and hence is not amenable to the solutions proposed in this report.

2.0 FACTORS AFFECTING BATCH FLUORIDATION

Adding fluoride to a water supply reservoir during the annual filling operation is conceptually very simple, but considerably more difficult in practice. Several complicating factors must be considered in designing a fluoridation system and in calculating the necessary fluoride dosage and feed rate. Some of these factors include: the reservoir layout, logistics, the freeze concentration of fluoride, ice growth, and reservoir drawdown. Each of these is discussed in detail below.

2.1 Reservoir Layout

The reservoirs considered in this study have some similarities, and several differences. Most of the reservoirs are filled once each year, generally in the late summer / early fall. In most instances the water source is some distance from the storage reservoir. Water is therefore pumped (or flows by gravity) through a pipeline from the source to the reservoir. The fill pumps (where used) are located at the water source and hence may be some distance from the reservoir. All of the reservoirs service a trucked water distribution system. Hence they all have a truckfill station, which houses the necessary equipment and instrumentation, near the reservoir edge.

Major differences between the reservoirs can be noted in: number of cells (one or two), reservoir shapes and dimensions, location

of the reservoir fill (influent) lines, and location of the reservoir effluent lines (drawing from the reservoir). The reservoir shape and dimensions determine the water depth versus water surface area and water depth versus water volume relationships, which can be used to determine the reservoir drawdown over time (see section 2.5).

In most of the reservoirs, the reservoir fill line discharges over the edge of the reservoir berm. This line may discharge to air, with the water running down the side of the berm, or it may float on the rising water surface of the reservoir. An alternative arrangement found in Tuktoyaktuk and Fort Good Hope, has the influent line passing through the truckfill station and discharging at the bottom of the reservoir. In the first arrangement, the influent and effluent lines may be close together or far apart, while in the second arrangement, the influent and effluent lines are generally adjacent. The position of the influent line discharge will influence the mixing of the reservoir during filling. The degree of mixing will also be affected by the reservoir geometry and weather conditions.

The relative positions of the influent and effluent lines will influence the degree of "short circuiting" which may occur when the reservoir is being filled and drawn from simultaneously. With the influent and effluent lines close together, one might expect greater short-circuiting when water is drawn from the

reservoir during the filling operation. This may be significant if fluoride is being added at relatively high concentrations in the reservoir fill line.

Where the reservoir fill line passes through the truckfill station, access is available to the line for fluoride injection. In this instance, the truckfill station provides a secure, sheltered, climate controlled environment in which to set up equipment and store chemicals. This is not possible when the influent line discharges over the reservoir edge, generally some distance from the truckfill station.

Reservoirs also vary in the amount of instrumentation available. Most have some sort of volumetric metering device on the effluent line in the truckfill station. Very few provide any indication of the volume of water pumped into the reservoir, or of the depth or volume of water in the reservoir at any time.

2.2 Logistics

Design and implementation of projects in the north can be greatly complicated by numerous logistics problems. Some of these must be considered in the design of a batch fluoridation system. First, one must consider the availability, transportation and handling of fluoride chemicals. Hydrofluosilicic acid (HFSA) is recommended over sodium fluoride or sodium silicofluoride, since it does not require mixing on site. Mixing powdered chemicals is

potentially hazardous and requires some degree of skill. Operators with sufficient skill to manage the operation may not be available in many communities.

The acid is available from chemical suppliers in several locations in Canada, including Edmonton, Montreal and Toronto. Chemicals for use in Tuktoyaktuk and Fort Good Hope are probably best purchased from Edmonton, while the Eastern Arctic communities could be supplied from Toronto or Montreal. HFSA is considered a hazardous good (because of its corrosive properties), and hence cannot be shipped by air in appreciable quantities. Thus it must be transported by truck, rail or ship. Fluoride shipments must therefore be arranged well in advance to ensure delivery at the necessary time. Hydrofluosilicic acid is generally sold in 140 kg barrels (approximately 25 Imp. gallons). It may be very difficult to handle such heavy containers, particularly if lifting equipment is not available. Thus, it may be advisable to arrange for purchase and shipment of the acid in smaller, more easily handled containers (eg. 5 or 10 gallons). Arrangements must also be made to store the acid once it arrives in the community. It may be necessary to store surplus and/or partly full containers from one year to the next.

The acid will be fed into the reservoir fill line using a variable flow metering pump. Such pumps require 110 volt AC power. Hence, an appropriate power supply must be available at,

or near the point of fluoride injection. Arrangements should also be made for pump repair or replacement services. Because of the difficulty of site repair work in remote locations, it may be advisable to keep several back-up pumps available in some central location (eg. Yellowknife or Iqaluit). These could be shipped to a community, as needed, on relatively short notice.

Finally, it is desirable to be able to monitor the fluoride concentration in the reservoir during the filling operation. The necessary laboratory facilities are available in very few locations in the N.W.T. The time necessary for sample transportation and analysis is likely in the order of several days. Because more rapid feedback regarding fluoride concentration is desirable, a portable fluoride analysis kit, for on-site use, is recommended. Such kits are available from the Hach Chemical Co. (and other suppliers) and are relatively straightforward to use.

2.3 Freeze Concentration of Fluoride

Observations of natural systems and considerable experimental work (eg. Fertuck, 1968 and 1969) indicate that most ions are rejected from freezing water, producing ice which is relatively pure. The more slowly ice is formed, the more efficient this process becomes. The net result of this "freeze concentration" phenomenon is that ions become concentrated in the water

remaining below the ice. Thus, if fluoride is added to reservoir water once each year, (generally in late summer / early fall) its concentration will increase as the reservoir freezes. One must ensure that the initial (full reservoir) fluoride concentration does not produce a concentration, in the unfrozen portion of the reservoir, above the recommended maximum of 1.6 mg/l, under maximum expected ice conditions.

Marianayagam (1986) reports that there is no accurate method of predicting what fraction of the fluoride will be excluded from the ice and concentrate in the water remaining in the reservoir. Since the available evidence indicates that a great percentage of the ions in solution are rejected from freezing water, it was assumed, during this study, that ice is completely free of fluoride. This conservative assumption implies that 100% of the fluoride will be rejected from freezing water and concentrate in the water remaining in the reservoir.

2.4 Ice Growth

To predict the freeze concentration of fluoride, one must first predict the ice thickness at various times through the winter (eg. monthly). A number of methods are available, as outlined in the Cold Climate Utilities Delivery Manual (EPS, 1986). One of the simplest, and most widely used is Stephan's equation. In this equation, ice thickness is calculated as a function of the number of degree-days below 0^{o}C. It is generally accepted that

the equation overpredicts ice thickness, since it does not account for the insulating effect of any snow cover, which acts to reduce ice growth. The equation can be modified (somewhat arbitrarily) to account for snow cover.

In the absence of the necessary meteorological information (i.e. degree-days below $0^{o}C$) one can predict the pattern of ice growth over time, from an assumed maximum ice thickness. Since ice growth follows a fairly predictable pattern, one can essentially fit a typical curve between zero ice and the expected maximum ice thickness. The expected maximum may be based on local observations or on the value used in the design of the reservoir.

These three methods are illustrated in more detail by Murray (1987). The Stephan equation predictions, generally being the most conservative (i.e. predicting greatest ice growth) were used in this study. An example of these predictions is included in Appendix A.

2.5 Reservoir Drawdown

The water surface elevation of the reservoir is affected by two dynamic factors, ice growth and water consumption. Under conditions of ice build-up, the water surface of the reservoir is the underside of the ice. To predict the fluoride concentration in the reservoir at any time, the reservoir water volume must be known. The change in reservoir volume with time can be

calculated using a dynamic drawdown analysis. This analysis requires knowledge of: ice growth, water consumption, water depth versus surface area, and water depth versus reservoir volume relationships. The analysis is illustrated in some detail in Appendix A.

2.6 Summary of Information Requirements/Calculations

The previous sections described several factors which must be considered in designing a fluoridation system, and calculating the appropriate initial fluoride concentration. The subsequent section will outline the design of two fluoridation systems. The information and calculations required to determine the fluoride dosage are summarized below. These steps are illustrated in Appendix A.

(1) Determine the current fluoride concentration in the reservoir, and in the water source (i.e. from which the reservoir is filled).

(2) Determine, from as-built drawings and design reports, the reservoir dimensions, cross section, etc. Use these to develop water depth versus surface area and water depth versus reservoir volume relationships.

(3) Determine the average monthly water consumption from the reservoir. This may vary considerably from month to month.

(4) Calculate monthly ice growth using any or all of the methods mentioned in Section 2.4.

(5) Perform dynamic drawdown analysis to determine the expected reservoir volume in each month (see Appendix A).

(6) Determine the appropriate initial (full reservoir) fluoride concentration, so that the maximum fluoride concentration (expected in late Spring) does not exceed the permissible concentration of 1.6 mg/l. This requires a trial and error approach as outlined in Appendix A.

3.0 CONCEPTIONAL DESIGN OF BATCH FLUORIDATION SYSTEMS

The batch fluoridation system design follows that presented by Marianayagam (1986). In essence, the system consists of a variable flow rate pump which feeds hydrofluosilicic acid from a shipping container or feed tank into the reservoir influent line during reservoir filling. In this way, fluoride is added to, and mixed intimately with, all of the water entering the reservoir. The mixing of the influent with water already in the reservoir will be determined by other factors, as mentioned previously.

The HFSA should only be injected into the influent line when the reservoir is actually filling. Mechanical problems such as pump failure, line break, etc. resulting in loss of influent flow are sometimes encountered during reservoir filling. To prevent feeding HFSA during periods of no flow, a flow switch is included in the system. This device senses flow/no-flow conditions, and switches off the power to the fluoride feed pump in the event of a no-flow condition. In those installations lacking flow meters on their influent lines, a flow indicator/totalizer, with a low-flow alarm condition could be installed. Such a device would be more complicated and expensive than a simple flow switch, but it would provide considerable, useful information.

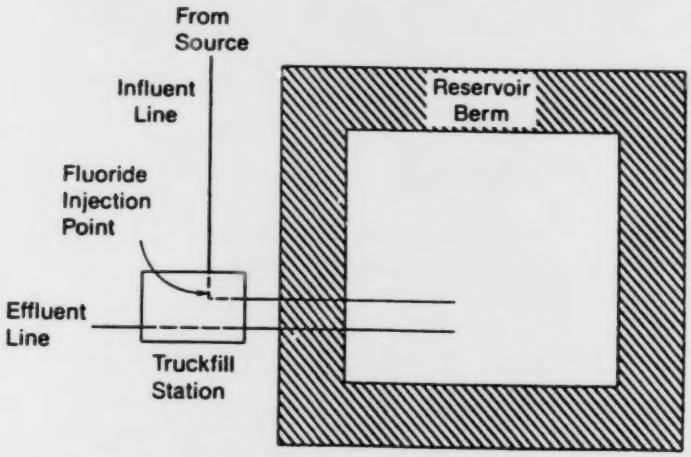
The basic conceptual design is affected by the layout of the reservoir influent line. In those installations where the

influent line passes through the truckfill station, the necessary equipment can be set-up inside the truckfill station. However, in most cases, the influent line discharges directly to the reservoir side or surface and does not pass through the truckfill station. An alternative design is required in this case. Conceptual designs for both alternatives are presented in the following sections.

3.1 Indoor Fluoridation System

Where the reservoir influent line passes through the truckfill station, all the equipment can be set up securely inside the truckfill station. The indoor fluoridation system is illustrated schematically in Figure 3.1. This system is recommended for use in Tuktoyaktuk and Fort Good Hope. As indicated, the acid is pumped from a feed tank into the influent line. The recommended pump is a Wallace & Tiernan Series 45 Chempulse Pump (or equivalent). It has a manually controlled, variable discharge rate with a maximum capacity of 1 U.S gallon per hour (3.78 l/hour), and a maximum discharge pressure of 150 psi. The 50 U.S. gallon feed tank is not essential, since HSFA could be fed directly from the shipping containers into the influent line. However, if HFSA is supplied in small containers, it may be more convenient to transfer the acid into the feed tank, to avoid having to change the feed container frequently. In any case, the feed tank is constructed of clear plastic, which permits visual monitoring of the volume of acid added to the reservoir. This

(a) Layout



(b) Fluoride Feed System

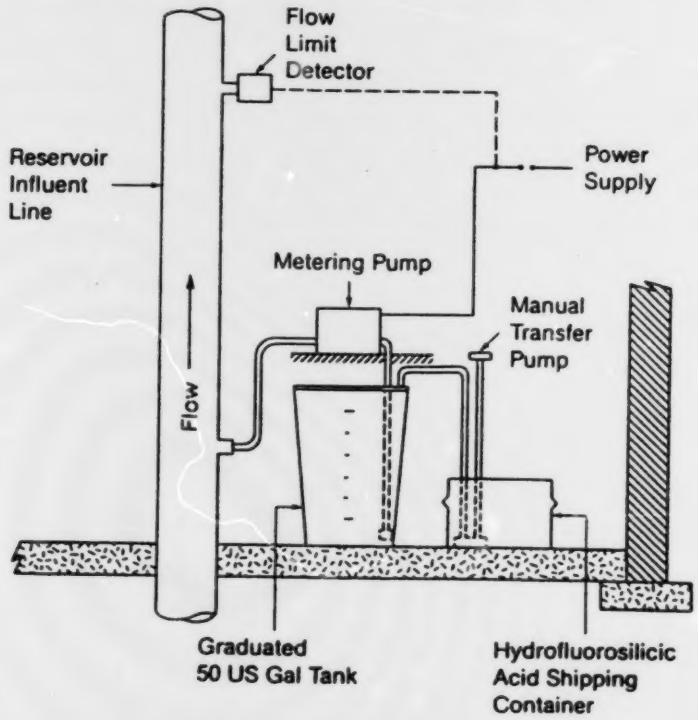


Figure 3.1

Indoor Fluoridation System

provides a quick, although not very accurate, check on the acid volumetric feed rate.

The system is designed to avoid feeding fluoride if the influent flow stops for any reason. The flow switch used to detect low-flow (or no-flow) conditions may or may not include indications of instantaneous and cumulative volumetric flow. Finally, provision is made for a sampling point, downstream of the fluoride injection point. This feature is not essential, but is recommended to facilitate the monitoring and control of the fluoride addition.

3.2 Outdoor Fluoridation System

Design and implementation of batch fluoridation is somewhat more difficult when the reservoir fill line does not pass through the truckfill system. In this case, there are several possible fluoridation alternatives, including:

(1) Install fluoridation equipment along with the reservoir fill pump at the water source. However, these locations are often difficult to access, and very rarely have an appropriate power supply.

(2) Install fluoridation equipment inside truckfill station: run the fluoride pump discharge line along the reservoir edge to an injection point in the influent line. However, both the feedback from the flow switch (which would be installed on the influent line), and the fluoride pump discharge line

would be exposed for a considerable distance. Although reservoirs are generally enclosed by a fence, there is the possibility of these lines being disturbed (by small ground animals, etc.). Interruption of the flow switch signal would not be particularly serious, but a break in the fluoride line might have undesirable consequences.

(3) Install fluoridation equipment on the edge of the reservoir, adjacent to the influent time, as it enters the reservoir. Power to this installation would have to be supplied from the truckfill station by a temporary power line laid on the ground. This power line would be vulnerable to the same disruption mentioned above. The equipment and chemical feed tank could be housed in a small locked enclosure, on the edge of the reservoir.

Of the three alternatives, the first is not promising because of the power supply problem. Both the second and third have some merits, as well as disadvantages. The third alternative (equipment installed at the reservoir edge) is preferred, because only the power line must be laid on the ground between the influent line and the truckfill station. A schematic illustration of such an outdoor fluoridation system is presented in Figure 3.2. This system is recommended for use in Pangnirtung, Broughton Island, Igloolik, Eskimo Point, and Coral

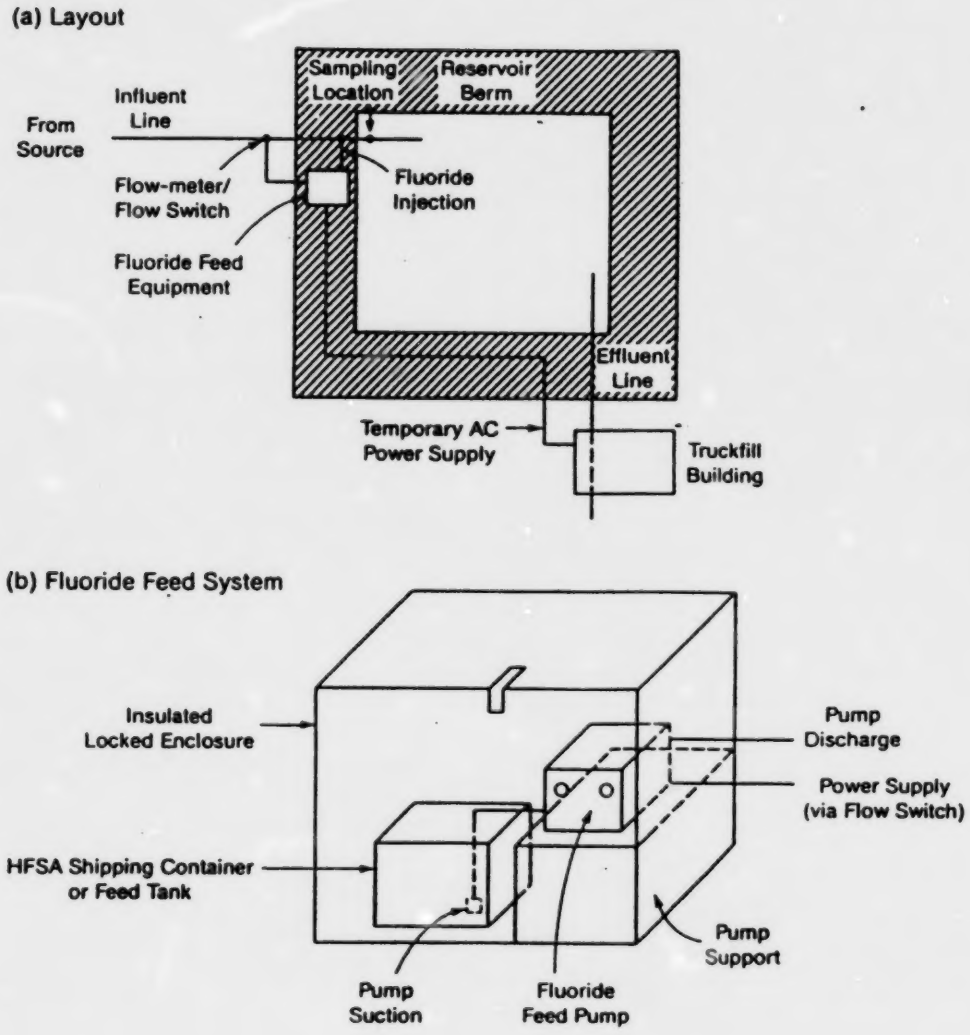


Figure 3.2

Outdoor Fluoridation System

Harbour. Grise Fiord, because of its unique water supply system, requires a slightly modified system, as outlined by Murray (1987).

As indicated in Figure 3.2, all of the fluoridation equipment would be housed in a locked enclosure. The enclosure should be waterproof, but does not have to be heated. Although freezing conditions are not expected in late summer / early fall, it might be prudent to insulate the enclosure. The enclosure would house an acid feed container (5 to 10 gal. size), the fluoride injection pump, and any necessary instrumentation for the flow switch. The recommended pump is the same Wallace & Tierman Chemical Feed Pump (or equivalent) mentioned in the previous section. Acid could be fed either from the shipping container, or from a small feed tank. Feeding from the shipping container eliminates the need for transfering the acid between containers, but may require more operator attention to ensure that sufficient acid supply is always available to the pump.

This system would require constructing 2 or 3 access points (taps) in the influent line, near the reservoir edge. A totalizing flow indicator with a low-flow alarm should be installed in the most upstream point. The second point would be the flouride injection point. The third point would be a sampling location. It should be located sufficiently downstream of the injection point (i.e. closer to the reservoir), to ensure

adequate mixing of the HFSA with the influent water prior to sampling.

This fluoridation system could be constructed on site, or fabricated in a central location and then shipped to the community. It is envisioned that the enclosure would be self-contained and easily transported. All related equipment (eg. power cord, flow meter, etc.) could be stored inside the box when not in use. Each community should have its own system. Identical equipment (pump, flow meter, etc.) should be used in the construction of each system. Spare parts should then be ordered and stored in a central location available to all communities, as required.

3.3 Miscellaneous Requirements

As well as the equipment just described, several other items are needed to safely and successfully implement batch fluoridation. These include:

(1) Measuring instruments. Adding the proper amount of fluoride will generally require measuring a specified amount of HFSA from the shipping container. The acid can be measured by weight (using a scale) or by volume (using a volumetric cylinder). Appropriate materials for handling and storing HFSA include rubber lined steel, 316 stainless, polyethylene, PVC, Kynar & Hypalon.

(2) Personal Safety Equipment. Hydrofluosilicic acid is corrosive and must be handled as a hazardous chemical. When

handling HFSA (eg. transfering from shipping container to feed tank, rinsing containers, etc.), workers should wear chemical resistant gloves, aprons, goggles and face shields.

(3) Fluoride Analysis Kit. It is important that the progress of fluoride addition be monitored to ensure that the desired fluoride concentrations are achieved and maintained. A portable analysis kit, with pre-measured reagent ampoules is available from the Hach Chemical Company .

(4) Chemical Transfer Equipment. If the HFSA is to be transferred from the shipping containers to a feed tank, the necessary equipment must be available. Transfer may be done using manual chemical hand pumps or siphons.

3.4 Fluoride Feed Rate

Once the necessary calculations are performed, the required fluoride supplement determined, and the fluoride feed system set up, the fluoride feed rate must be established. There are several alternative fluoride feed strategies. The fluoride might be added over a short time (eg. several days) at the maximum rate permitted by the fluoride feed pump (eg. 1 U.S. gallon/hour). Depending on the influent water flow rate, this might produce a relatively high fluoride concentration in the influent. If there is already an appreciable volume of water in the reservoir, if the influent mixes rapidly with the reservoir contents and if the effluent line is some distance from the influent line, then little "short circuiting" would be expected. In this case, a

high influent concentration should not produce a (temporary) high effluent concentration, and rapid fluoride feed would be an acceptable strategy. If this approach is taken, the fluoride should be added rapidly near the end of the reservoir filling operation, to ensure that there is sufficient water in the reservoir to dilute the high fluoride concentration influent.

However, if there is a possibility of short circuiting occurring (eg. adjacent influent and effluent lines, poor mixing, etc.), then the fluoride should be added at a lower feed rate over most of the reservoir filling period. The approximate time required for the reservoir filling can be predicted from the initial and (expected) final reservoir volumes and the capacity of the reservoir filling pumps. The design fluoride feed time should be somewhat (eg. 1 - 2 days) shorter than the expected filling time, to allow for start-up and any operational problems. The fluoride feed rate is then simply the required fluoride volume or mass divided by the design fluoride feed time.

If one is unsure about the degree of mixing and dilution likely to occur in the reservoir, then a relatively low initial fluoride feed rate should be selected. Subsequent monitoring of the reservoir effluent will indicate the amount of mixing and dilution taking place in the reservoir. If the fluoride concentration of the reservoir effluent is well below the maximum allowable concentration (1.6 mg/l), then the fluoride feed rate might be increased.

A sample calculation for the fluoride (HFSA) required when filling a reservoir is presented in the companion report "Tuktoyaktuk Reservoir Fluoridation Operations Manual."

3.5 Sampling

During the fluoride addition, samples of the reservoir influent and effluent should be collected and analyzed on a regular basis. The fluoride concentration of the influent should be relatively constant, as long as the filling rate is constant and the fluoride feed rate is constant. The rate of fluoride addition can be calculated if the influent fluoride concentration and reservoir filling rate are known. The actual rate of addition can then be checked against the design fluoridation rate.

Samples of the water drawn from the reservoir (the effluent) can be taken at the truckfill station. These samples are important, since they indicate the fluoride concentration of the water being consumed in the community. The fluoride concentration in the reservoir effluent will increase from some background value (approximately 0.1 mg/l for a reservoir which has never been fluoridated) to the desired full reservoir fluoride concentration over the course of the reservoir filling. The effluent fluoride concentration will generally be considerably less than the influent fluoride concentration (because of dilution effects), and should always be below the recommended maximum of 1.6 mg/l.

4.0 IMPLEMENTATION OF BATCH FLUORIDATION

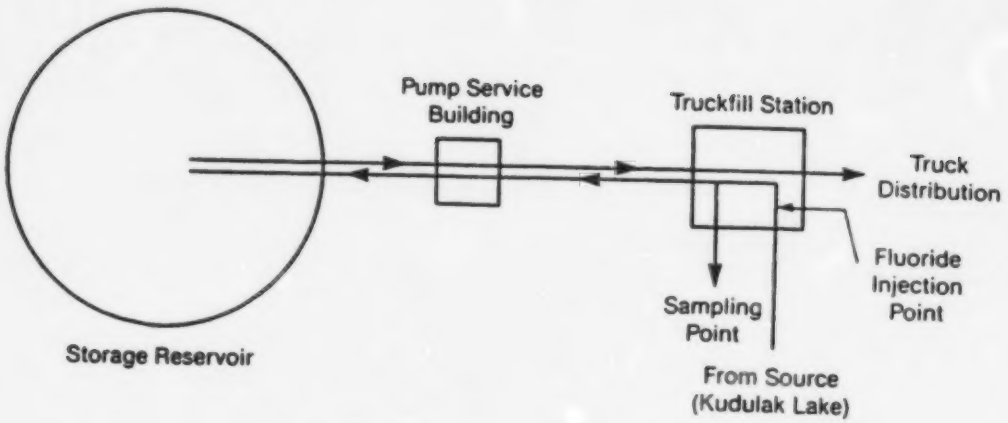
4.1 Background

Marianayagam (1986) recommended Tuktoyaktuk as a potential site for the first application of batch fluoridation. In April, 1987, the Hamlet council authorized the fluoridation of Tuktoyaktuk's water supply reservoir. This provided an opportunity to demonstrate the technology of batch fluoridation. The fluoridation of the Tuktoyaktuk reservoir is described in detail by Murray (1987), and summarized below.

The current water supply system in Tuktoyaktuk was completed in late 1985. It consists of an intake and pumping unit at the source (Kudulak Lake), a supply pipeline to the water storage reservoir, and a truckfill station and pump service building adjacent to the reservoir. Several of these components are illustrated schematically in Figure 4.1 (a). The reservoir is a circular, lined structure constructed from sand dredged from Tuktoyaktuk harbour. It is filled in late summer/early fall each year from Kudulak Lake. This water has a fluoride concentration of 0.1 mg/l (Marianayagam, 1986). The portable pumping unit at the lake has a capacity of approximately 1 million Imperial gallons per day (52.5 l/s) (Reagan, 1987).

As outlined previously, the calculation of the required fluoride supplement involved the following steps:

(a) Schematic Layout



(b) Acid Feed System — Truckfill Station

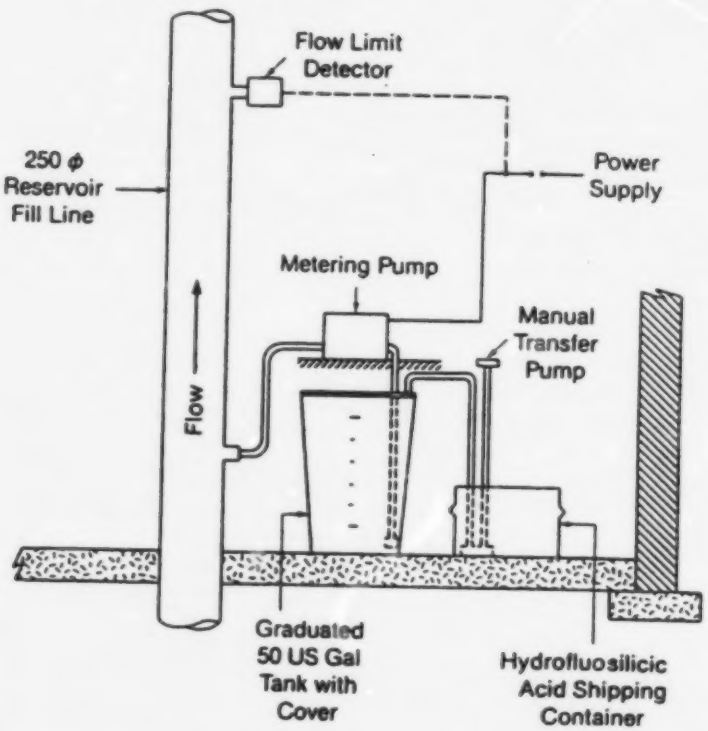


Figure 4.1

Tuktoyaktuk Water Fluoridation System

- determine the fluoride concentration in the reservoir,
- determine the fluoride concentration in the water supply to be used to fill the reservoir,
- determine monthly water consumption,
- determine reservoir volume prior to filling,
- calculate expected monthly ice growth,
- determine depth/area/volume relationships from reservoir dimensions,
- calculate the expected monthly reservoir volumes (i.e. reservoir drawdown),
- perform iterative fluoride freeze concentration calculations to determine the highest full reservoir fluoride concentration which will not produce a maximum (late spring) fluoride concentration above 1.6 mg/l, and
- determine the fluoride supplement, and feed rate necessary to reach the desired fluoride concentration.

All of these calculations are illustrated in Appendix A.

The calculations indicated that the reservoir should be fluoridated to a concentration of 0.8 mg/l. Allowing for the freeze concentration effects, it was estimated that this would produce a maximum (late spring) fluoride concentration between 1.46 and 1.57 mg/l (depending on water consumption).

4.2 Fluoridation System

Hydrofluosilicic acid (HFSA), as a 25% solution (by weight), was used as the source of fluoride ion. The fluoride was injected

into the reservoir fill line inside the truckfill station, as indicated in Figure 4.1(a). The feed system is illustrated in more detail in Figure 4.1(b). The acid was first transferred from the shipping containers to the graduated plastic drum, using a manual acid transfer pump. The feed pump then drew the acid from the plastic tank and injected it into the 250 mm diameter fill line. The feed pump was a Wallace and Tiernan Series 45 Chempulse pump. It had a manually controlled, variable discharge rate, with a maximum capacity of 1 US gallon per hour, and a maximum discharge pressure of 150 psi.

The fluoride solution was added fairly continuously during the reservoir filling. The filling operation took approximately 15 days, and fluoride was added over 10 days.

The feed system was designed to avoid feeding fluoride if the reservoir fill pump stopped for any reason. A non-invasive sonic flow switch was used to sense flow/no flow conditions. If the flow in the fill line stopped, the flow switch would automatically cut off the power supply to the fluoride feed pump.

The reservoir fluoridation proceeded quite smoothly. With minor exceptions, the equipment functioned as expected, and produced the expected results. A routine monitoring program is now in place which will facilitate the comparison of actual observations with predicted values (e.g. ice growth, fluoride concentrations, etc.).

4.3 Experience Gained from the Field Trial

The field trial demonstrated the feasibility of batch fluoridation and provided some valuable operational experience with the process. The success of the reservoir fluoridation was due partly to good planning and careful monitoring of the operation. Some of the lessons learned from the field trial, ranging from quite general to very specific, are summarized below.

(i) Good planning is essential to the success of the operation. All necessary equipment must be available on-site prior to the start of reservoir filling and fluoridation. The planning should include contingency plans for equipment breakdown, etc.

(ii) Cooperation between all parties involved in the reservoir filling and fluoridation is very important. During the field trial, there was constant communication between the author, the reservoir filling contractor and local DPW staff. Cooperation and communication must be maintained.

(iii) Fluoride chemicals (hydrofluosilicic acid) should be ordered well in advance. Chemicals are more easily handled in small containers than in large containers.

(iv) The fluoride feed system proved to be very effective. The feed pumps must be calibrated under operating conditions (against the actual flow in the reservoir influent line).

(v) The flow switch was a convenient feature which eliminated many concerns about accidental shut-downs. The sonic flow switch served its purpose, but may be inappropriate for many applications. Either a more sensitive sonic-type switch, or a conventional in-line flow meter should be used in future applications.

(vi) The initial and final reservoir volumes are important design parameters. Unfortunately, they may be very difficult to estimate accurately. Effort should be made to estimate reservoir volumes as accurately as possible. Influent and effluent totalizing meters are very useful in this regard.

(vii) The sampling results indicated that the Tuk reservoir was fairly well mixed throughout the fluoridation operation. Thus the fluoridated influent was diluted and dispersed very rapidly and no short circuiting problems were noted. Although it is difficult to generalize from these results, one might expect similar patterns in other applications. If mixing is rapid and no short circuiting occurs, the fluoride feed rate is not very critical. The necessary volume of HFSA might be added over a much shorter time than in the field trial.

(viii) It is probably not possible for all future reservoir fluoridations to be as closely supervised and monitored as the Tuk field trial. Knowledgable, skilled individuals should be involved in the design phase, calculating the required fluoride supplements for each application. The

implementation can then be done by local DPW staff. All personnel involved in the implementation should be given a short training program to provide the necessary background.

5.0 DISCUSSION

5.1 Reservoir Design Considerations

Any reservoirs and truckfill stations designed or upgraded in the future should incorporate features to facilitate water fluoridation. Several such features are outlined below.

(i) The reservoir influent line should be routed through the truckfill station. This permits easy access to the line for fluoride injection and provides a secure, sheltered location in which to set-up equipment and store chemicals.

(ii) Volumetric totalizing meters should be installed on the influent and effluent lines. This will provide an indication of the reservoir volume at any time.

(iii) A flow meter/low-flow alarm switch should be installed on the influent line. Instruments are available which provide flow indications as well as low-flow alarms.

(iv) At least two pre-tapped holes (approximately 25mm in diameter) should be provided on the influent line, inside the truckfill station. One would serve as a fluoride injection point, and the second would be used for drawing samples of the fluoridated influent water.

(v) Truckfill stations should be designed to include:

- running water (for rinsing equipment, etc.),
- sufficient space to set up fluoride feed equipment and store chemicals,
- 110 volt A.C. power outlet.

Most existing truckfill stations have these facilities.

5.2 Potential Remedial Measures

The batch fluoridation approach should be a safe and effective means of adding fluoride to year-round water storage reservoirs. However, human mistakes and mechanical failures are always possible, and should be anticipated. Two types of failures can be envisioned in the fluoridation operation. The first would involve human or equipment failure, or calculation error leading to a less than optimal addition of fluoride. This is not a serious situation. Either more fluoride could be added manually to the full reservoir or the community could forego the benefits of fluoridated water for one year.

The second type of failure, which would lead to a greater than optimum addition of fluoride is somewhat more serious, but not likely dangerous. Long term consumption of greater than optimum amounts of fluoride produces mottling of the teeth, which may be unsightly, but is not life threatening. If too much fluoride were added to a reservoir, several remedial measures could be taken to improve the situation:

(i) Some water could be drained from the reservoir and more fresh water added to dilute the remaining fluoride.

(ii) More water could be added without draining the reservoir. This would cause the reservoir water level to rise to at least the overflow drains (if present).

(iii) An attempt could be made to de-fluoridate the water. A number of defluoridation methods are described and evaluated in a report by Sollo et al (1978). Fluoride removal methods can be divided into two groups: (a) precipitation methods based on the addition of chemicals to the water, and (b) methods in which the fluoride is removed by adsorption or ion exchange on a suitable material.

The entire contents of the reservoir could be treated by adding chemicals such as alum (as a coagulant), phosphates (to form a fluorapatite precipitate), or magnesium (to remove fluoride by adsorption on magnesium hydroxide precipitate).

Alternatively, the water drawn from the reservoir could be passed through a column in which fluoride was removed by an appropriate material. Adsorption on activated alumina has been shown to be an effective method for fluoride removal. The process is currently used in several locations in the United States (Sollo et al,1978).

5.3 Administration / Logistics of Batch Fluoridation

The Tuk field trial demonstrated that batch fluoridation is technically feasible. Thus, fluoridation of water storage reservoirs now becomes primarily an administrative and logistical challenge rather than a technical one. The design and

implementation of the field trial involved the time and effort of one person essentially full time for more than one month. This is not feasible as a routine approach to water fluoridation. Arrangements will have to be made between GNWT Department of Municipal and Community Affairs (MaCA) and Public Works (DPW) personnel in Yellowknife, the regional centres and individual communities for batch fluoridation to be performed efficiently and effectively on an annual basis.

As indicated throughout this report, there are two distinct sets of activities in performing batch fluoridation. One involves calculating the required fluoride supplement for each application. This must be done for each community, each year, and requires some fairly detailed information from the community. These calculations might best be done by the MaCA Regional Engineers for the communities in each region. The results could then be communicated to Regional DPW Engineers. Alternatively, the calculations, etc. could be the responsibility of the Regional DPW Engineers.

The second set of activities are concerned with the implementation phase. All of the necessary equipment and supplies must be purchased, shipped to the communities and installed. This must take place prior to the start of reservoir filling. The necessary design, ordering, and fabrication of equipment, and ordering of chemicals should be the responsibility

of Regional DPW Personnel. Where appropriate, these activities might be delegated to DPW staff in the communities. The actual implementation and monitoring of the reservoir fluoridation is probably best done by DPW staff in each community, under the supervision of DPW engineers. Detailed notes should be kept each year and made available to all interested parties.

Regardless of the actual division of activities, it is important that responsibilities for the various aspects of batch fluoridation be explicitly assigned to specific groups or individuals. Only in this manner will water fluoridation cease to be a novelty or a "special study" and become an accepted aspect of municipal services provided to the communities. Numerous details will have to be resolved in the first few years of such a fluoridation program, but it should soon become a routine annual procedure.

5.4 Areas Requiring Further Work

In addition to resolving and assigning administrative responsibilities, further work is necessary in at least two other areas, namely the promotion of water fluoridation, and follow-up monitoring and surveys. The report by Marianayagam (1986), and an earlier section of this report outlined the very poor state of dental health in the N.W.T. This situation can be improved in several ways: by altering dietary habits, by improving oral hygiene and by increasing fluoride consumption to an optimum

level. To bring about change in any of these areas will require public education campaigns by various government departments, both at the Federal and Territorial levels.

Most of the population in general, and community leaders in particular may be unaware of the benefits of consuming fluoridated water. If they are aware of the dental health benefits of fluoride, they may be unaware that water fluoridation is technically feasible in their communities. Unless one, or more, government departments make an effort to inform the communities about the benefits and availability of water fluoridation, the communities are unlikely to request and/or approve fluoridation. However, it is not clear where the initiative for promoting community water fluoridation should lie. The necessary education and training should perhaps be jointly sponsored by Health and Welfare Canada, and the GNWT Department of Municipal and Community Affairs. In any case, this matter must be resolved before water fluoridation will become widely accepted and practiced in the N.W.T.

The second area requiring further work is in follow-up monitoring and surveys. As mentioned in a previous section, the fluoride concentration of the reservoir water must be monitored fairly regularly following batch fluoridation. It would also be extremely informative to perform regular dental health surveys. Since water fluoridation requires a certain investment in time

and money, it would be useful to determine its effectiveness in reducing tooth decay in Northern communities. Dental health surveys should be done before initiating fluoridation in a community and at regular intervals thereafter. Alternatively, or additionally, one might examine dental health in several communities not practicing fluoridation. A comparison with demographically similar communities having fluoridated water supplies would provide an indication of the effectiveness of water fluoridation in the North. Such dental health surveys should be sponsored by Health and Welfare Canada. The communities might be selected in consultation with MaCA. A dental health survey in Tuktoyaktuk should be initiated <u>now</u>.

6.0 SUMMARY AND RECOMMENDATIONS

The high incidence of tooth decay in the N.W.T., particularly among native people, is a cause for considerable concern. Tooth decay can be reduced by a combination of good nutrition, improved oral hygiene and the use of fluoride supplements. The normal dietary intake of fluoride can be supplemented in several ways to help reduce tooth decay. The most equitable, effective and efficient method is to add a controlled amount of fluoride to community water supplies. Because of the variety of water supply systems in the N.W.T., various techniques of water fluoridation are required.

In those communities with water storage reservoirs which are filled once each year (i.e. provide year-round storage), a batch fluoridation approach is recommended. The proposed system uses hydrofluosilicic acid (HFSA) as the fluoride source. The HFSA would be fed by a positive displacement, variable flow pump from a shipping container or feed tank into the reservoir influent line during reservoir filling. A flow switch would prevent fluoride addition if the influent flow to the reservoir stopped for any reason. This system ensures good mixing of the fluoride with the reservoir water, and requires supervision for only 2 or 3 weeks each year, while the reservoir is filled. One drawback to the approach is that the fluoride concentration in the reservoir water will increase throughout the winter as ice forms

on the reservoir. The initial fluoride concentration must be selected with this in mind. N.W.T. regulations recommend a fluoride concentration between 1.2 and 1.6 mg/l with 1.4 mg/l considered optimum.

The calculation of the appropriate fluoride dose requires information such as:

- the fluoride concentration of the water source and the existing reservoir water,
- the depth/area/volume relationships for the reservoir,
- the monthly water consumption from the reservoir, and
- the expected monthly ice growth on the reservoir.

This information must be updated, and the calculations repeated prior to each application. As part of this study, the necessary information was collected, and design and calculations performed for eight communities, namely: Tuktoyaktuk, Fort Good Hope, Pangnirtung, Broughton Island, Eskimo Point, Igloolik, Coral Harbour and Grise Fiord. The details are presented in a report by Murray (1987).

A recent field trial in Tuktoyaktuk demonstrated the feasibility of batch fluoridation. Using the fluoridation system described in the report, the reservoir water was fluoridated to a concentration of 0.8 mg/l over approximately 10 days. This is expected to result in a maximum (late winter) fluoride concentration well below the 1.6 mg/l maximum. Monitoring of the

reservoir fluoride concentration over the year should confirm these predictions.

From the work done during this study, a number of recommendations can be made. These are presented below:

(i) Effort should be made, by appropriate government agencies, to promote and improve dental health in the N.W.T. These efforts should include public education campaigns aimed at improving diet and hygiene, and the promotion of water fluoridation.

(ii) Community leaders in those communities where batch fluoridation is feasible should be informed about the benefits and feasibility of water fluoridation.

(iii) Further, detailed studies should be done regarding fluoridation in communities with partial water treatment (disinfection) and no year-round reservoir storage. These communities include a significant percentage of the N.W.T. population.

(iv) Follow-up monitoring should be done in Tuktoyaktuk, following the recent fluoridation of the reservoir. Water samples should be collected weekly (at the truckfill station) and analyzed for fluoride concentration. It may also be useful to install ice-depth gauges, or otherwise monitor ice thickness throughout the winter. A baseline dental health survey should be done as soon as possible. Dental health surveys in subsequent years would then provide

an indication of the effectiveness of water fluoridation in reducing tooth decay.

(v) Batch fluoridation in other communities should follow the designs presented in the report. Good planning and preparation are essential for the success of any fluoridation program.

(vi) The N.W.T. government should resolve the administrative responsibilities for future fluoridation programs. It is important that responsibilities be clearly defined and assigned to specific groups or individuals.

(vii) All personnel to be involved in the implementation of batch fluoridation should be given a short training seminar to familiarize them with the necessary concepts and technology.

(viii) Any reservoirs and truckfill stations designed or upgraded in the future should incorporate features to facilitate water fluoridation. Such features include:

- reservoir influent line routed through truckfill station,
- volumetric totalizing meters on the influent and effluent lines, and
- two or three pre-tapped holes in the influent line for installing fluoridation equipment.

7.0 REFERENCES

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APPENDIX A

EXAMPLE CALCULATIONS
TUKTOYAKTUK RESERVOIR FLUORIDATION

A.1 WATER SUPPLY SYSTEM

The current Tuktoyaktuk water supply system was completed in late 1985. It consists of an intake and pumping unit at the source (Kudulak Lake), a supply pipeline to the water storage reservoir and a truckfill station and pump service building adjacent to the reservoir. Several of these components are illustrated schematically in Figure A.1 (a). The reservoir is a circular, lined structure constructed from sand dredged from Tuktoyaktuk harbour. Its dimensions are shown on Figure A.1 (b) (Marianayagam, 1986), and include:

- Inside bottom diameter = 104.4 m
- Maximum water depth = 7.0 m
- Design ice thickness = 2.1 m
- Dead storage depth = 0.5 m

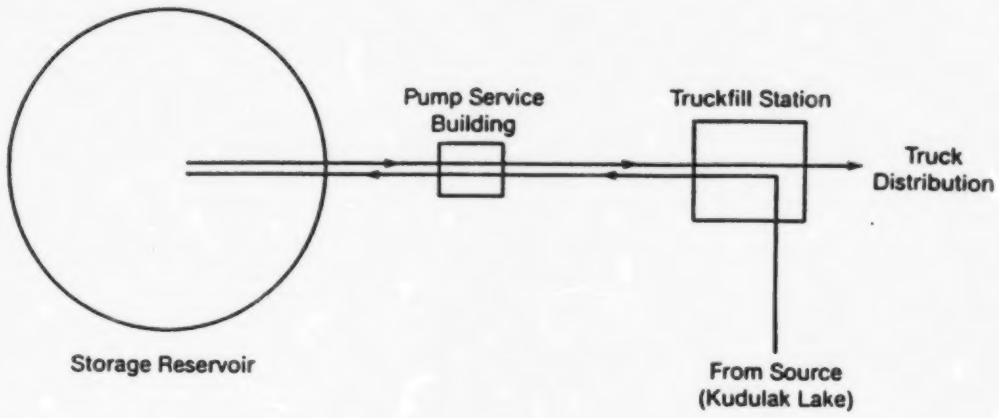
The reservoir is filled in late summer/early fall each year from Kudulak Lake. This water has a fluoride concentration of 0.1 mg/l (Marianayagam, 1986). The portable pumping unit at the lake has a capacity of approximately 1 million Imperial gallons per day (52.5 l/s) (Reagan, 1987).

A.2 CALCULATION OF REQUIRED FLUORIDE SUPPLEMENT

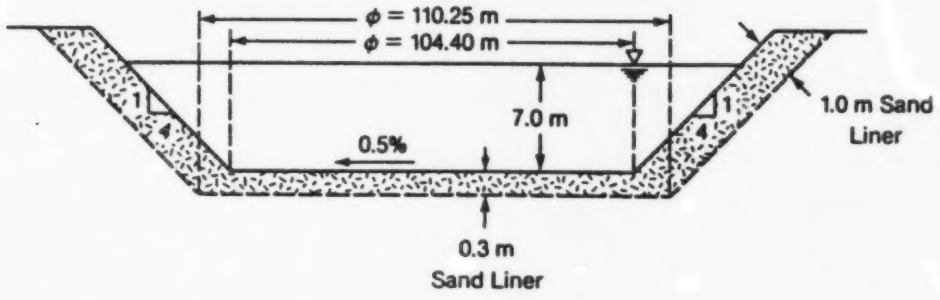
As outlined previously, the calculation of the required fluoride supplement involves the following steps:

- determine the fluoride concentration in the reservoir,
- determine the fluoride concentration in the water supply to be used to fill the reservoir,

(a) Schematic Layout



(b) Typical Reservoir Cross Section



Source: Marianayagam (1987)

FIGURE A.1

TUKTOYAKTUK WATER SUPPLY SYSTEM

- determine monthly water consumption,
- determine reservoir volume prior to filling,
- calculate expected monthly ice growth,
- determine depth/area/volume relationships from reservoir dimensions,
- calculate the expected monthly reservoir volumes (i.e. reservoir drawdown),
- perform iterative fluoride freeze concentration calculations to determine the highest full reservoir fluoride concentration which will not produce a maximum (late spring) fluoride concentration above 1.6 mg/l, and
- determine the fluoride supplement, and feed rate necessary to reach the desired fluoride concentration.

All of these calculations are illustrated in some detail below.

A.2.1 Water Consumption

An analysis of water use from the Tuk reservoir is presented in Table A.1. Included in the table are actual and design estimates of monthly water use. Although the actual monthly water use information is not complete, it indicates a definite trend. Through 1986 the average actual water use was similar to the design value of 5381 m^3/month. However, following the decrease in industrial activity in late 1986, the water use has decreased significantly, to about 2250 m^3/month. Since it is difficult to predict the pattern of future consumption, the design calculations were done for two scenarios:

TABLE A.1

RESERVOIR WATER USE: TUKTOYAKTUK

	1985	1986	1987
Actual Water Use (m3/month) (from Hamlet records)			
JAN.		3803	?
FEB.		3301	2062
MAR.		?	2319
APRIL		4161	2300
MAY		6137	2242
JUNE		6701	
JULY		7198	
AUG.		6552	
SEPT.		?	
OCT.	?	?	
NOV.	?	?	
DEC.	3627	?	
Design Water Use (m3/month) (EPEC,1980)			
Hamlet		3489	3604
Other		1892	1892
Total		5381	5496

TABLE A.2

MONTHLY ICE GROWTH: TUKTOYAKTUK

Month	Degree Days <0C	Cumul've DD<0C	Ice Thickness @ Month End (m) Stephan Eq'n	Modified Stephan	Assuming 2.1 m max.
August	0.0	0.0	0.00	0.00	0.00
September	17.1	17.1	0.14	0.14	0.09
October	240.4	257.5	0.54	0.54	0.43
November	587.1	844.6	0.98	0.83	0.87
December	780.8	1625.4	1.36	1.14	1.27
January	882.2	2507.6	1.69	1.40	1.58
February	821.0	3328.6	1.95	1.60	1.80
March	823.6	4152.2	2.18	1.76	1.94
April	514.5	4666.7	2.31	1.85	2.04
May	163.0	4829.7	2.35	1.88	2.10
June	5.8	4835.5	0.00	0.00	0.00
July	0.0	4835.5	0.00	0.00	0.00

- high water use 5500 m^3/month
- low water use 2500 m^3/month

A.2.2 Current Reservoir Volume

The reservoir volume prior to filling was estimated in two different ways. The first estimate was obtained using the readings on the totalizing bulk meters on the reservoir fill line and the truckfill line. These readings were as follows (June'87):

meter reading on reservoir fill line (i.e. cumulative water added to reservoir) = 134,010 m^3 (1)

meter reading on truckfill line (i.e. cumulative water drawn from reservoir) = 77,922 m^3 (2)

Thus the indicated reservoir volume was ((1) - (2)), or 56,088 m^3.

The second estimate was made from a measurement of the reservoir depth. The water depth at the center of the reservoir in early July was 4.5 m (15 ft.). Using the relationship between reservoir water depth and volume (equation A.2), a reservoir volume of 53,330 m^3 is indicated. These two estimates are very similar. Allowing for water consumption during July, an initial reservoir volume (prior to filling) of 50,000 m^3, was assumed in the following design calculations.

A.3.3 Ice Growth

Monthly ice growth was estimated using three different approaches, namely: the Stephan equation, a modified version of the Stephan equation which considers the insulating effect of

snow cover, and an empirical approach based on the design maximum ice thickness (2.1 m) (see Murray, 1987). The results generated using all three methods are summarized in Table A.2. The Stephan equation results were generated from a record of degree-days below 0°C for Tuktoyaktuk, which was obtained from Environment Canada (AES, 1982). The Stephan equation, which ignores possible insulation by snow-cover, predicts a maximum ice thickness of 2.35 m, somewhat more than the design ice thickness of 2.1 m (EPEC, 1982). The Stephan equation results, being the most conservative were used in the subsequent calculations. However, either of the other sets of figures could be used, to produce less conservative, and possibly more realistic results.

A.2.4 Depth / Area / Volume Relationship

Schematic drawings of the Tuk reservoir were presented in Figure A.1. For calculation purposes, the reservoir can be considered as a truncated cone, with a 52.2 m radius base, and 4:1 sideslopes. The free surface area and volume of a truncated cone can be calculated as a function of its depth:

$$\text{Area } (m^2) = \pi(52.2 + 4h)^2 \qquad (A.1)$$

$$\text{Volume } (m^3) = \pi h/3\ [52.2^2 + (52.2 + 4h)^2 + (52.2)(52.2 + 4h)] \qquad (A.2)$$

Where:

h = water depth (at reservoir center) (m)

A.2.5 Dynamic Drawdown Analysis

Under conditions of ice build-up, the water surface of the reservoir is the underside of the ice. The water surface elevation is affected by two dynamic factors, ice growth and water consumption. Water consumption and monthly ice growth predictions were presented in Tables A.1 and A.2 respectively. Using this information, and equations (A.1) and (A.2) the reservoir drawdown was calculated as indicated in Table A.3 (a and b) (for the high and low water use cases respectively). Although the notes provided on the table indicate the calculations being performed, several sample calculations are provided below, to illustrate the technique further. The calculations are for the high water use case (Table A.3 (a)) and assume that the reservoir is at its maximum depth (7.0 m) at the end of August. This assumes that the reservoir is filled to its design maximum depth of 7.0 m during August.

(i) September

(a) Water Consumption = 5500 m^3/month (high water use assumption)

(b) Initial water level (at beginning of month) = 7.0 m (reservoir assumed full at end of August)

(c) Water surface area (from equation A.1) $= (52.2 + (4)(7.0))^2$ $= 20197\ m^2$

(d) Drop in water level due to water consumption $= \frac{\text{volume consumed per month}}{\text{water surface area}} = \frac{5500\ m^3}{20197\ m^2} = 0.27$ m

(e) Ice thickness at month end (from Stephan eq'n prediction; Table A.2) = 0.14 m

TABLE A.3
RESERVOIR DRAWDOWN: TUKTOYAKTUK

(a) High Water Use

Month	(1) Water Consump'n (m3)	(2) Initial WL (m)	(3) WS Area (m2)	(4) WL Drop via WC (m)	(5) Ice @ ME (m)	(6) Increm'l IceGrowth (m)	(7) Final WL (m)	(8) Final Volume (m3)	(9) Volume in Ice (m3)
August	5500	-	-	-	0.00	0.00	7.00	97851	0
September	5500	7.00	20197	0.27	0.14	0.14	6.59	89693	2705
October	5500	6.59	19375	0.28	0.54	0.40	5.90	76848	9963
November	5500	5.90	18045	0.30	0.98	0.44	5.16	63927	17282
December	5500	5.16	16656	0.33	1.36	0.38	4.45	52543	23127
January	5500	4.45	15382	0.36	1.69	0.33	3.76	42375	27805
February	5500	3.76	14197	0.39	1.95	0.26	3.12	33562	31182
March	5500	3.12	13129	0.42	2.18	0.23	2.47	25400	33937
April	5500	2.47	12100	0.45	2.31	0.13	1.88	18574	35404
May	5500	1.88	11205	0.49	2.35	0.04	1.35	12830	35820
June (10)	5500	1.35	10422	0.53	0.00	0.00	3.81	43150	0
July	5500	3.81	14281	0.39	0.00	0.00	3.42	37701	0

(b) Low Water Use

Month	Water Consump'n (m3)	Initial WL (m)	WS Area (m2)	WL Drop via WC (m)	Ice @ ME (m)	Increm'l IceGrowth (m)	Final WL (m)	Final Volume (m3)	Volume in Ice (m3)
August	2500	-	-	-	0.00	0.00	7.00	97851	0
September	2500	7.00	20197	0.12	0.14	0.14	6.74	92596	2746
October	2500	6.74	19669	0.13	0.54	0.40	6.21	82452	10239
November	2500	6.21	18631	0.13	0.98	0.44	5.63	72070	17946
December	2500	5.63	17538	0.14	1.36	0.38	5.11	63152	24243
January	2500	5.11	16571	0.15	1.69	0.33	4.63	55393	29418
February	2500	4.63	15705	0.16	1.95	0.26	4.21	49001	33270
March	2500	4.21	14974	0.17	2.18	0.23	3.82	43220	36525
April	2500	3.82	14298	0.17	2.31	0.13	3.51	38924	38329
May	2500	3.51	13784	0.18	2.35	0.04	3.29	35911	38865
June (10)	2500	3.29	13418	0.19	0.00	0.00	5.65	72276	0
July	2500	5.65	17568	0.14	0.00	0.00	5.51	69874	0

NOTES:

(1) high or low water use assumption

(2) assumes: reservoir filled to 7.0 m depth in August
subsequent months; initial water level = water level at previous month end

(3) water surface area from equation (A.1)

(4) water consumption/water surface area

(5) ice thickness at month end (Stephan eq'n prediction from Table A.2)

(6) ice @ current month end - ice @ previous month end

(7) = (2) - (4) - (6)

(8) reservoir water volume from equation (A.2)

(9) cumulative volume of water = water surface area @ final depth (eq (4.1)) + incremental ice growth + previous volume in ice
stored in ice

(10) June final water volume = May final volume - consumption + May volume in ice
June final water level found by trial and error using final volume and Eq (A.2)

(f) Incremental ice growth during month
= (ice at current month end - ice at previous month end)
= 0.14 - 0 = 0.14 m

(g) Water level at month end
= initial water level - drop via water cons'n - ice growth
= 7.0 - 0.27 - 0.14 = 6.59 m

(h) Water volume at month end (from eq'n A.2)
$= 6.59\pi/3\,[52.2^2 + (52.2 + 4(6.59))^2 + (52.2)(52.2 + 4(6.59))]$
$= 89695\ m^3$

(i) Volume of water stored in ice
= water surface area at final depth * incremental ice growth
$= [\pi(52.2 + (4)(6.59))^2]*0.14$
$= 2705\ m^3$

(ii) October

(a) Water Consumption = 5500 m^3/month (high water use assumption)

(b) Initial water level (at beginning of month) = 6.59 m (= water level at end of August)

(c) Water surface area (from equation A.1) $= \pi(52.2 + (4)(6.59))^2$
$= 19375\ m^2$

(d) Drop in water level due to water consumption
$= \frac{\text{volume consumed per month}}{\text{water surface area}} = \frac{5500\ m^3}{19375\ m^2} = 0.28$ m

(e) Ice thickness at month end = 0.54 m
(from Stephan eq'n prediction; Table A.2)

(f) Incremental ice growth during month
= ice at current month end - ice at previous month end
= 0.54 - 0.14 = 0.40 m

(g) Water level at month end
= initial water level - drop via water cons'n - ice growth
= 6.59 - 0.28 - 0.40 = 5.91 m

(h) Water volume at month end (from eq'n A.2)
$= 5.91\pi/3\,[52.2^2 + (52.2 + 4(5.91))^2 + (52.2)(52.2 + 4(5.91))]$
$= 76961\ m^3$

(i) Cumulative volume of water stored in ice
= water surface area at final depth * incremental ice growth
+ previous volume stored in ice
$= [\pi(52.2 + (4)(5.91))^2]*0.40 + 2705$
$= 9963\ m^3$

Any differences between these and the values tabulated on Table A.3 are due to the use of different numbers of significant figures in the calculations. The calculations illustrated above are the same for all subsequent months, except June. The ice is assumed to melt during June, converting the entire volume of water stored in ice back into liquid water. Thus the reservoir volume at the end of June (assuming all ice melted) is calculated as follows:

June volume = May volume - consumption + May volume stored in ice

The water level at the end of June is calculated by trial and error, using Equation (A.2) and the June water volume. The July calculations are the same as for the other months.

A.2.6 Freeze Concentration of Fluoride

As described previously, fluoride will be rejected from the ice as the reservoir freezes, and will concentrate in the water remaining in the reservoir below the ice. The concentration of fluoride in the reservoir water at any time is a function of the initial fluoride concentration, the water consumption from the reservoir and the reservoir volume. It is calculated as:

$$C(t) = \frac{C(t-\Delta t)\ [2V(t-\Delta t) - Q\Delta t]}{2V(t) + Q\Delta t} \qquad (A.3)$$

Where:

$C(t), C(t-\Delta t)$ = fluoride concentrations at times t and t- t (mg/l)

$V(t), V(t-\Delta t)$ = reservoir volume at times t and t- t (l)

Δt = time step (e.g. 1 month)

Q = rate of water withdrawal from reservoir (l/month)

The fluoride concentration in the month that the reservoir is filled (e.g. August) is specified (i.e. design full reservoir fluoride concentration), and the fluoride concentration in subsequent months is calculated using equation (A.3). The freeze concentration of fluoride in the Tuktoyaktuk reservoir is illustrated in Table A.4 (a) and (b) (for the high and low water use cases respectively), for initial fluoride concentrations of 0.8 and 1.0 mg/l.

Thus, in Table 4.4(a) (high water use case), for a full reservoir (August) fluoride concentration of 0.8 mg/l, the September fluoride concentration is:

$$C(t) = \frac{0.8\,[2(97800) - (5500)(1)]}{2(89612) + (5500)(1)}$$
$$= 0.823 \text{ mg/l}$$

Similarly, in October:

$$C(t) = \frac{0.82\,[2(89612) - (5500)(1)]}{2(76779) + (5500)(1)}$$
$$= 0.896 \text{ mg/l}$$

The calculations are the same for all months until ice melt occurs in June.

The results in Table A.4 (a) and (b) indicate that, for both cases (high and low water use), an initial fluoride concentration of 1.0 mg/l produces winter fluoride concentrations greater than the recommended 1.6 mg/l, for four months (February to May). However, an initial concentration of 0.8 mg/l produces a maximum concentration of less than 1.6 mg/l. If the low water use scenario were realized, the initial fluoride concentration could

TABLE A.4

FLUORIDE FREEZE CONCENTRATION: TUKTOYAKTUK

(a) High Water Use

Month	Water Consumed (m3)	Reservoir Volume (m3)	Fluoride Conc'n (mg/l)	Fluoride Conc'n (mg/l)
August	5500	97800	1.00	0.80
September	5500	89693	1.03	0.82
October	5500	76848	1.12	0.90
November	5500	63927	1.25	1.00
December	5500	52543	1.38	1.10
January	5500	42375	1.52	1.22
February	5500	33562	1.66	1.33
March	5500	25400	1.82	1.46
April	5500	18574	1.93	1.55
May	5500	12830	1.96	1.57
June	5500	43150	0.43	0.34
July	5500	37701	0.43	0.34

(b) Low Water Use

Month	Water Consumed (m3)	Reservoir Volume (m3)	Fluoride Conc'n (mg/l)	Fluoride Conc'n (mg/l)
August	2500	97800	1.00	0.80
September	2500	92596	1.03	0.82
October	2500	82452	1.12	0.90
November	2500	72070	1.24	0.99
December	2500	63152	1.37	1.09
January	2500	55393	1.49	1.20
February	2500	49001	1.61	1.29
March	2500	43220	1.73	1.38
April	2500	38924	1.81	1.44
May	2500	35911	1.83	1.46
June	2500	72276	0.86	0.69
July	2500	69874	0.86	0.69

be increased to approximately 0.85 mg/l. However, an initial (full reservoir) fluoride concentration of 0.8 mg/l was recommended, since this would produce acceptable concentrations, even if water use were to increase significantly.

A.2.7 Required Fluoride Supplement

The fluoride supplement required to produce a full reservoir fluoride concentration of 0.8 mg/l was calculated as outlined below. A number of assumptions were used in making these calculations. While they were appropriate for the 1987 reservoir fluoridation, they would have to be verified and/or modified prior to fluoridation in subsequent years.